Stereocontrolled Cationic Copolymerization of Vinyl Ethers

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Abstract:

Polymer tacticity has a profound influence on macroscopic material properties, including the thermal, mechanical, and optical behavior of a material. Despite advancements in coordination-insertion polymerization methods used for the synthesis of stereoregular poly(alpha-olefin)s, polar isotactic polymers have remained a challenging synthetic target. Previously, the Leibfarth group developed a method using the principles of asymmetric ion pairing catalysis to perform the stereoselective cationic polymerization of alkyl vinyl ethers. Homopolymerization of these initial monomers with a chiral BINOL-based phosphoric acid in combination with a titanium Lewis acid proved the promise of this approach to synthesize a unique class of polar, semi-crystalline thermoplastics. Herein, we provide a further expansion of this method through copolymerization, enabling the systematic tuning of both glass transition (T_g) and melting temperature (T_m). Key structure-reactivity relationships for this catalyst system were also established when copolymerizing an alkyl vinyl ether with a variety of functional group rich vinyl ether monomers.

Introduction:

A material's overall mechanical and thermal properties are influenced by its tacticity, the spatial arrangement of functional groups along a polymer backbone.[1] This difference is exemplified in the comparison of isotactic and atactic polypropylene, both synthesized from the same monomer. The stereoregularity present in the isotactic polymer, whereby all pendant functionality is on the same face of the macromolecular backbone, allows the polymer chains to

favorably pack together through intermolecular forces. This provides a highly desirable semi-crystalline polymer with a high melting temperature (T_m). These properties enable isotactic polypropylene to be one of the most common commercial plastics derived from crude oil, with applications ranging from food packaging to medical devices.[2] In contrast, the stereorandom microstructure in atactic polypropylene results in a material that is a viscous liquid with subpar thermal and mechanical properties.

Propylene and other nonpolar vinyl monomers are typically polymerized through a coordination—insertion mechanism with a catalyst that controls the facial approach of each monomer onto the growing prochiral polymer chain end.[2] Despite the success of isotactic polypropylene, stereocontrolled polymerization of polar vinyl monomers remains a largely unsolved challenge.[3] Lewis basic functional groups can coordinate with and poison early transition metal catalysts.[4,5] To address this limitation, late transition metal catalysts have been developed, but still lack necessary stereocontrol and catalyst activity. Because the inherent polarity found on chemical building blocks derived from nature are not amenable to coordination—insertion polymerization, their stereocontrolled polymerization is an outstanding challenge.

Vinyl ethers have been identified as a target polar vinyl monomer for accessing the desired thermomechanical properties of polyolefins while incorporating polarity and functionality. Currently, vinyl ethers are derived from an inexpensive feedstock and have greater potential for synthesis from biorenewable resources. Yet, commercial use of poly(vinyl ether)s (PVEs) is limited to lower value applications due to their amorphous nature as a result of their atactic microstructure.

Recently, the Leibfarth group has addressed the limitations described above through pioneering efforts on the stereocontrolled cationic polymerization of vinyl ether monomers.[6] In order to bring a chiral environment into close proximity to the polymerizing chain end, the method utilizes a titanium complex ligated by 1, 1'-bi-2-napthol (BINOL)-based phosphoric acid ligands (**1**). Using this Lewis acid catalyst enables the synthesis of isotactic PVEs with high stereoselectivity. Preliminary work exploring the monomer scope of this new methodology revealed high isotacticity for a range of vinyl ether monomers with short alkyl substitution. The thermal properties of the resultant semicrystalline materials were found to be closely linked to the identity of the side-chain. Linear alkyl substituents resulted in an isotactic PVE with T_m values ranging from 65 to 76°C, while branched substituents led to T_m values ranging from 138 to 152°C.

Herein, we report a systematic evaluation of copolymerization of branched and linear alkyl vinyl ethers to leverage the disparity in T_m's to allow for the tuning of thermal properties for this new class of polar thermoplastics.[7] Additionally, copolymerization of an alkyl vinyl ether with a series of functional group rich vinyl ethers was also performed to further expand the monomer scope of **1**.[8]

Methods:

All vinyl ether monomers were dried over CaH_2 and distilled under vacuum prior to storage in a N_2-filled glovebox freezer before further use. Reagents whose syntheses are not described below were purchased from commercial sources and used without purification. (R)-3,3'-bis(3,5-bis(trifluoromethyl)phenyl)-1,1'-binaphthyl phosphate[9] and tetrachlorobis(tetrahydrofuran) titanium(IV) ($TiCl_4(THF)_2$)[10] were synthesized according to previously publish literature.

Synthesis of 2-methoxy ethyl vinyl ether (MOVE):

In an oven dried 100 mL round bottom flask equipped with a stirbar, MeI (20.8 mL, 334 mmol) was added to a stirring slurry of ethylene glycol vinyl ether (15.0 mL, 167 mmol) and KOH (10.32 g, 184 mmol) at 0 °C. After 30 min the ice bath was removed and the reaction stirred at room temperature for 3 h before water (20 mL) was added. After stirring for a further 30 min the organic phase was separated and washed with water (20 mL), then dried over $MgSO_4$, and the solvents removed on a rotary evaporator at room temperature. Distillation under reduced pressure gave the title compound and confirmed by ^{1}H NMR matching literature spectra.[11]

Synthesis of 2-phenoxy ethyl vinyl ether (PhOVE):

In an oven dried 100mL round bottom flask equipped with a stirbar, to a toluene solution (27.0 mL) of $[IrCl(cod)]_2$ (0.184 g, 0.274 mmol) and Na_2CO_3 (1.744 g, 16.45 mmol) were added ethylene glycol monophenyl ether (3.44 mL, 27.42 mmol) and vinyl acetate (5.05 mL, 54.84 mmol) under N_2. The reaction mixture was stirred at 100°C for 2 hr. After quenching with diethyl ether and water, the product was purified by SiO_2 column chromatography with 9:1 hexane:EtOAc comprising mobile phase to afford pure product as a colorless liquid, and ^{1}H NMR matched literature spectra.[12]

Synthesis of 2-acetoxy ethyl vinyl ether (AcOVE):

In an oven dried 200 mL round bottom flask equipped with a stirbar, to a solution of ethyleneglycol monovinyl ether (2 g, 22.70 mmol), pyridine (2.75 mL, 34.05 mmol) and DMAP (0.277 g, 3.27 mmol) in anhydrous DCM (60 mL) was added Ac_2O (3.2 mL, 34.05

mmol). The mixture was stirred for 1 h 30 at room temperature then poured into a mixture of water (100 mL) and sat. aq. NaHCO3 (100 mL) which was extracted with DCM (40 mL then 2 x 100 mL). The organic layers were combined, dried over $MgSO_4$ and concentrated via rotary evaporation. The crude material was purified by SiO_2 column chromatography with 9:1 hexane:EtOAc comprising mobile phase to afford pure product as a colorless liquid. ^{1}H NMR matched previously reported specta.[13]

Synthesis of 2-benzoyloxy ethyl vinyl ether (BzOVE):

To an oven-dried 50 mL round bottom flask equipped with a stirbar was added dry sodium benzoate (1.587 g, 10.94 mmol), 2-chloroethyl vinyl ether (5 mL, 49.23 mmol), and trimethylamine (0.11 mL, 0.766 mmol). The solution was refluxed gently for 24 hr at 100°C, and the crude material was purified by SiO_2 column chromatography with 9:1 hexane:EtOAc comprising mobile phase to afford pure product. ^{1}H NMR matched previously reported spectra.[14]

Synthesis of 2-(vinyloxy)ethyl 4-methylbenzenesulfonate:

To an oven-dried 250 mL round bottom flask equipped with a stir bar, was added ethylene glycol vinyl ether (2.5 mL, 27.25 mmol), triethyamine (11.6 mL, 68.0 mmol), a catalytic amount (0.013 g, 0.111 mmol) of dimethylaminopyridine, and 25 mL dichloromethane and cooled in an ice bath. Tosyl chloride (6.375 g, 33.44 mmol) was dissolved in 50 mL dichloromethane in a 100 mL oven-dried round bottom flask and added via drop funnel under one hour of stirring. After stirring at room temperature for 24 hrs, the reaction mixture was washed with water, dried with $MgSO_4$, and dried via rotary evaporation to isolate a colorless liquid that matched with reported ^{1}H NMR literature spectra.[15]

Synthesis of 2-methoxy-4-methyl-phenoxy ethyl vinyl ether (MOPhOVE):

To an oven-dried 100 mL round bottom flask equipped with a stir bar was added 2.18 mL (17.2 mmol) creosol, 4.75 g (34.4 mmol) potassium carbonate, and 35 mL acetonitrile under inert atmosphere. The reaction vessel was cooled to 0 °C in an ice water bath, and 2-(vinyloxy)ethyl 4-methylbenzenesulfonate was added dropwise. Once the addition was complete, the ice water bath was removed, and the solution was allowed to warm to room temperature over 30 minutes. The reaction vessel was then heated to 50 °C in an oil bath and allowed to stir for 18 hours. Next, the reaction was removed from the oil bath, allowed to cool to room temperature, and volatiles were removed via rotary evaporation. The crude material was dissolved in dichloromethane and washed with water and brine. The dichloromethane was then removed via rotary evaporation, and the crude material was purified by SiO_2 column chromatography with 9:1 hexane:EtOAc comprising mobile phase to afford pure product as a colorless liquid. ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.83 (d, J = 8.0, 1H), 6.74 – 6.63 (m, 2H), 6.55 (dd, J = 14.3, 6.8, 1H), 4.27 – 4.18 (m, 3H), 4.09 – 4.01 (m, 3H), 3.85 (s, 3H), 2.30 (s, 3H). ^{13}C NMR (151 MHz, $CDCl_3$) δ 151.58, 149.43, 145.68, 131.49, 120.74, 114.40, 112.87, 86.65, 67.76, 66.16, 55.73, 20.98. IR (neat): 2940 (w), 1619 (m, C=C), 1512 (s), 1457 (m), 1414 (w), 1322 (m), 1265 (s, C-O), 1236 (s, C-O), 1199 (s, C-O), 1159 (s), 1142 (s), 1035 (s), 982 (s), 796 (s) cm^{-1}.

General Copolymerization Procedure (1.0 mmol scale):

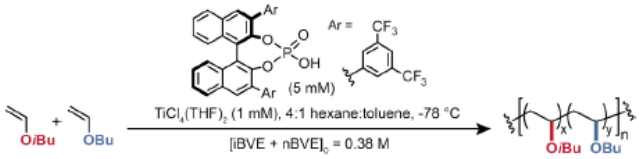
Copolymerizations were performed in 8 mL septum-capped reaction vials prepared in a N2-filled glovebox. An oven-dried 8 mL septum-capped vial equipped with a stir bar was charged with an appropriate volume of a 1.0 M iBVE stock solution in hexane, an

appropriate volume of a 1.0 M RVE stock solution in hexane, and 1.1 mL hexane such that the total volume was 2.1 mL. A separate 8 mL septum-capped vial equipped with a stir bar was charged with 0.26 mL of a 0.05 M stock solution of (R)-3,3'-bis(3,5-bis(trifluoromethyl)phenyl)-1,1'-binaphthyl in MePh (0.013 mmol) and 0.26 mL of a 0.01 M stock solution of $TiCl_4(THF)_2$ in MePh (0.0026 mmol). Both vials were removed from the glove box and cooled to -78 °C in a dry ice/acetone bath. After stirring at -78 °C for 20 min, the entire MePh solution was transferred via dry syringe to the vial containing monomer solution. The reaction was stirred at -78 °C for 4 h, after which 0.38 mL of Et_3N/MeOH solution (10% v/v) was added to quench the polymerization. Upon warming to room temperature, the mixture was washed with 1N HCl, and all volatiles removed in vacuo. The crude polymer was dissolved in 1–2 mL CH_2Cl_2 and filtered through a plug of SiO_2 (4-5 cm) in a glass pipette eluting with additional CH_2Cl_2. After removing CH_2Cl_2 via rotary evaporation, and precipitating into methanol, the resulting purified polymer was dried under vacuum for at least 12 h to a constant weight.

Tacticity and monomer incorporation ratios were confirmed with ^{1}H NMR and ^{13}C NMR. Thermal stability and thermal properties were determined by Thermal Gravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC). Molecular weight and dispersity were confirmed through Gel Permeation Chromatography (GPC).

Results and Discussion:

Due to the difference in thermal properties shown by isotactic PVE's derived from monomers bearing either branched or alkyl side chains, we first explored the copolymerization of butyl vinyl either (nBVE) with iBVE (Figure 1). High molecular weight polymers were obtained



f_{Bu} [a]	F_{Bu} [b]	M_n [c] (kg mol^{-1})	$Đ$ [c]	*m* (%)	T_g (°C) [d]	T_m (°C) [d]
0.05	0.11	72	1.7	92	-28	131
0.10	0.20	88	2.0	93	-22	122
0.20	0.30	121	2.0	94	-31	105
0.30	0.43	113	2.1	94	-37	89
0.40	0.54	157	2.4	94	-42	74
0.50	0.63	241	2.5	91	-45	63
0.60	0.74	238	2.4	94	-49	56
0.70	0.82	211	2.7	93	-55	57
0.80	0.87	211	2.7	92	-51	51
0.90	0.93	182	2.5	93	-56	53

[a] mole fraction of nBVE in the monomer feed. [b] mole fraction of nBVE in copolymer determined by ^{1}H NMR integration. [c] M_n indicates the number average molecular weight of the polymer. Dispersity was calculated according to $Đ = M_w/M_n$ where M_w is the weight average molecular weight. [d] T_g and T_m obtained from a second heating scan (10 °C/min) after the thermal history was removed.

Figure 1. Reaction scheme depicting the stereoselective copolymerization of iBVE and nBVE using **1** and a summary of copolymerization experiments.

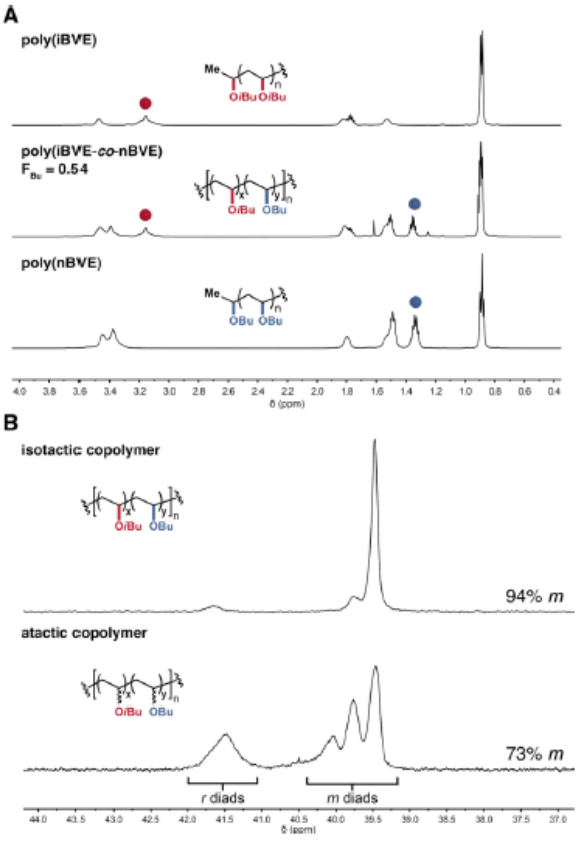


Figure 2. (A) ^{1}H NMR ($CDCl_3$) spectra of poly(iBVE) (top), poly(iBVE-co-nBVE) (middle), and poly(nBVE) (bottom) highlighting the distinct resonances observed for iBVE (red sphere) and nBVE (blue sphere) repeat units. (B) Observed differences of the backbone methylene ^{13}C NMR ($CDCl_3$) resonances in an isotactic poly(iBVE-co-nBVE) made using **1** and an atactic poly(iBVE-co-nBVE) made using trifluormethanesulfonic acid.

with high dispersity as a result of the uncontrolled chain-growth polymerization. The fraction of nBVE (f_{Bu}) relative to iBVE was systematically varied to tune the final incorporation of each in the resulting copolymers. Distinct ^{1}H NMR resonances for each comonomer repeat units were integrated relative to each other to determine the incorporated mole fraction (F_{Bu}), exemplified in Figure 2A. The copolymerization demonstrates a higher incorporated molar fraction of nBVE (F_{Bu}) relative to its feed ratio. The lower incorporation of iBVE is likely related to steric hindrance between the branched vinyl ether and **1**. Stereoselectivity was determined through ^{13}C NMR analysis by comparing the integration of the *racemo* diad region to the *meso* diad region (Figure 2B). High degrees of isotacticity (91-94% *meso* diads) were accessed through the use of catalyst **1** for synthesis of poly(iBVE-co-

f_{Et}[a]	F_{Et}[b]	M_n (kg mol^{-1})[c]	Đ[c]	m (%)	T_g (°C)[d]	T_m (°C)[d]
0.05	0.09	58	1.7	93	-26	132
0.10	0.13	58	1.9	93	-25	132
0.15	0.22	62	1.9	93	-29	107
0.20	0.34	83	2.0	92	-32	66
0.30	0.38	101	2.4	93	-33	50[e]
0.40	0.52	41	1.7	93	-37	39[e]
0.50	0.62	90	2.7	92	-37	40[e]
0.65	0.74	66	2.0	91	-37	not observed
0.8	0.83	51	1.8	93	-38	41[e]
0.9	0.91	82	2.6	92	-39	42[e]

[a] mole fraction of EVE in the monomer feed. [b] mole fraction of EVE in copolymer determined by 1H NMR integration. [c] M_n indicates the number average molecular weight of the polymer. Dispersity was calculated according to Đ = M_w/M_n where M_w is the weight average molecular weight. [d] T_g and T_m obtained from a second heating scan (10 °C/min) after the thermal history was removed. [e] T_m values obtained from first heating scan (10 °C/min) after annealing at room temperature for several days.

Table 1. Summary of copolymerization experiments with iBVE and EVE using **1**.

At room temperature, all copolymer samples were semicrystalline thermoplastics. Through DSC analysis, data showed the materials demonstrated T_g and T_m values spanning the range between those of poly(nBVE) (T_g = -53°C, T_m = 65°C) or poly(EVE) (T_g = -42°C, T_m = 76°C) and poly(iBVE) (T_g = -20°C, T_m = 138°C). As predicted by the Fox equation, the T_g decreases linearly as F_{Bu} or F_{Et} increases, with more agreement shown by the nBVE and iBVE copolymerizations (Figure 3). Importantly, the T_g remains well below room temperature, which is required for useful semicrystalline thermoplastics. The T_m values observed by DSC mostly decrease linearly with increasing linear vinyl ether incorporation. For TnBVE), highlighting the fact that the relative levels of branched or linear substitution did not significantly affect tacticity levels. Analogous copolymerizations of iBVE and EVE were also performed, yielding similar results (Table 1).

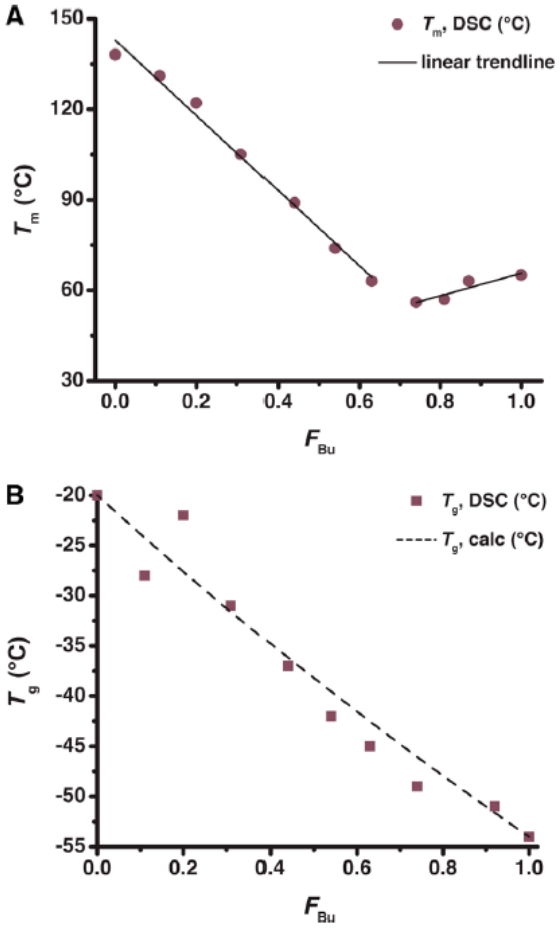
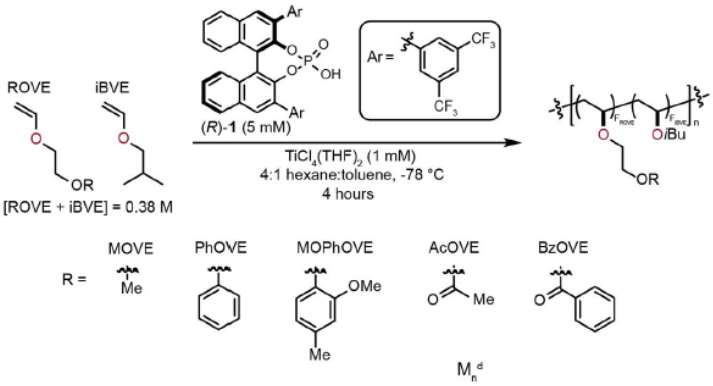


Figure 3. (A) Plot of T_m obtained by DSC as a function of molar incorporation of nBVE (F_{Bu}). Solid lines highlight observed trends. (B) Plot of T_g obtained by DSC as a function of F_{Bu}. Dashed line indicates T_g values predicted using the Fox equation.

poly(iBVE-co-nBVE), as F_{Bu} increases above $F_{Bu} = 0.7$, an inflection point occurs as a result of a composition switch from iBVE repeat units to nBVE repeat units dominating the crystalline regions. In regards to poly(iBVE-co-EVE) (Table 1), the T_m decreased concomitantly with increasing F_{Et} until plateauing at ~40°C when $F_{Et} \geq 0.5$. No T_m was reliably observed in the second heating cycle by DSC when $F_{Et} \geq 0.3$, although these materials crystallized slowly at room temperature and exhibited obvious first-order transitions in the first heating cycle. Despite these differences, the observed trends demonstrate that catalyst **1** allows for stereoselective copolymerization of nBVE or EVE with iBVE in order to afford a useful material with tunable T_g and T_m.

With the success of catalyst **1** for alkyl vinyl ethers, we sought to expand the scope to include more polar and functional monomers. A small library of vinyl ether monomers bearing different functionalities was synthesized in order to systematically investigate their individual structure-reactivity relationships with catalyst **1**. Using an ethylene glycol linker, the vinyl ether monomers were appended with functional groups similar to those seen in nature, such as aryl, ether, and ester groups (Figure 5). Initial homopolymerization of these monomers with catalyst **1** were not successful, likely due to interaction between the Lewis basic functionality with the oxophilic Ti Lewis acid. However, we hypothesized that copolymerization of these functional vinyl ethers in combination with an alkyl vinyl ether would maintain catalyst activity and stereoselectivity while still incorporating functionality. Similar to the above described copolymerizations, iBVE was used as a representative alkyl vinyl ether comonomer, and the library of various substituted oxyethylene vinyl ethers (ROVE, where R is a variable substituent)



Entry	ROVE	f_{ROVE}[a]	F_{ROVE}[b]	% conv[c]	M_n[d] (kg mol^{-1})	$Đ$[d]	*m* (%)[e]
1	MOVE	0.05	0.06	84	56	2.1	91
2	MOVE	0.15	0.16	85	68	1.4	89
3	MOVE	0.30	0.50	40	49	2.2	81
4	MOVE	0.40	0.70	18	32	1.6	72
5	PhOVE	0.05	0.06	61	74	2.1	89
6	PhOVE	0.15	0.07	60	47	1.9	88
7	PhOVE	0.30	0.09	41	54	1.9	89
8	PhOVE	0.40	0.13	39	42	1.7	90
9	PhOVE	0.50	0.22	29	39	1.6	90
10	MOPhOVE	0.05	0.04	50	69	2.1	92
11	MOPhOVE	0.15	0.05	47	52	1.8	90
12	MOPhOVE	0.30	0.05	48	36	1.7	90
13	MOPhOVE	0.40	0.07	25	30	1.5	91
14	AcOVE	0.01	0.02	70	72	2.1	92
15	AcOVE	0.03	0.09	35	47	1.8	83
16	AcOVE	0.05	0.12	20	35	1.6	85
17	BzOVE	0.01	0.03	38	75	2.0	92
18	BzOVE	0.03	0.09	18	47	1.8	93
19	BzOVE	0.05	0.15	7	50	1.6	87

Figure 5. Structure−reactivity analysis of functional comonomers bearing Lewis basic sites.

were used at a particular molar fraction (f_{ROVE}) relative to iBVE. The actual molar incorporation of ROVE (F_{ROVE}) was again calculated using relative integration of unique ^{1}H NMR resonances for the iBVE and ROVE repeat units.

First, we investigated the copolymerization of 2-methoxy ethyl vinyl ether (MOVE) with iBVE. When $f_{MOVE} \leq 0.20$, high monomer conversions (>73%) and isotactic copolymers (89-91% *m*) were observed, and F_{MOVE} remained similar to f_{MOVE}. Increasing f_{MOVE} to incorporate more MOVE resulted in significant decreases in monomer conversion and tacticity.

We next investigated phenoxy ethyl vinyl ether (PhOVE), which represents a phenyl ether functionality that is less Lewis basic than the alkyl ether in MOVE. As f_{PhOVE} increased, F_{PhOVE} consistently increased while overall monomer conversion decreased. High isotacticity (90% *m*) was maintained until F_{PhOVE} reached a maximum of 0.22, a higher level of functional comonomer incorporation then MOVE. Since phenyl ethers are prominent in numerous small molecule derivatives of lignin, we also chose to study a vinyl ether monomer derived from creosol as a representative lignin derivative. The vinyl ether monomer 2-methoxy-4-methyl-phenoxy ethyl vinyl ether (MOPhOVE) was synthesized and copolymerized with iBVE. At $f_{MOPhOVE} = 0.05$, we

observed 50% conversion and isolated a copolymer of $F_{MOPhOVE}$ = 0.04 and 92% *m*. Interestingly, increasing $f_{MOPhOVE}$ did not significantly influence $F_{MOPhOVE}$ or isotacticity. Overall, the phenyl ether substituents were tolerated better than the methyl ether group and enabled the incorporation of the lignin derived MOPhOVE into isotactic PVE copolymers.

To further expand the potential of isotactic PVEs as high-performance thermoplastics with significant potential for various applications, we investigated the tolerance of catalyst **1** for carbonyl containing vinyl ethers. Acetoxy ethyl vinyl ether (AcOVE) and benzoyl oxy ethyl vinyl ether (BzOVE) both represented simple ester containing monomers. Both monomers achieved much higher molar incorporation than f_{ROVE}. Addition of f_{AcOVE} = 0.01 resulted in F_{AcOVE} = 0.02 with high isotacticity (93% *m*) and monomer conversion (70%). The copolymerization of BzOVE and iBVE resulted in copolymers with moderate conversions (18-38%) and high isotacticities (92-93% *m*) when $F_{BzOVE} \leq 0.09$. For both ester containing monomers, when molar incorporation was increased, there was a significant loss in monomer conversion and tacticity.

Through studying this library of functional comonomers, we observed that more Lewis basic functionality reduces overall catalyst efficiency and stereoselectivity at high incorporations. However, incorporating phenyl groups can marginally mitigate this effect by increasing the steric environment and decreasing overall Lewis basicity of these vinyl ethers.

Conclusion:

Overall, we utilized catalyst **1** to synthesize a series of isotactic vinyl ether copolymers. Through choice of comonomers, the thermal properties, T_m and T_g, can be rationally tuned by adjusting the ratio of incorporation, while still maintaining high stereoselectivity. Additionally, the monomer scope of the catalyst was expanded to include more polar and functional polymers

through copolymerization with iBVE. We demonstrated structure-reactivity trends, establishing a promising foundation for the pursuit of a new class of bio-based plastics.

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